Compression Resistance Testing of Combat Helmets and the Effects on Ballistic Performance

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1. INTRODUCTION

With the current focus on weight reduction, combat helmets are evolving toward more technologically advanced laminate material systems which happen to have a lower stiffness in comparison with the traditional aramid helmets. Higher ballistic limit resistance – weight ratio have been obtained using Ultra High Molecular Weight Polyethylene (UHMWPE) fibres and advanced aramid fibre reinforced thermoplastic laminates. However, in both cases, there are concerns about the lower overall rigidity of the resulting helmet shells and the effect this may have on the performance of the helmet over its life cycle. Quantification of helmet stiffness would be valuable to prevent permanent deformation under normal use to a point where safety and operability are compromised. The challenge is to define requirements that ensure soldier's safety for a loading that is representative of what a helmet may experience in day to day training and combat activities. Underestimated requirements can reduce the helmet life cycles and put the soldier at risk. On the other hand, overestimated rigidity requirements can increase helmet weight needlessly and be detrimental to the operational effectiveness of the soldier.

2. BACKGROUND

Helmet rigidity requirements exist for a variety of industrial safety, motorcycle, equestrian, and combat helmets. In the product specifications reviewed, test samples are evaluated in three different orientations. These include front to back (longitudinal), side to side (lateral) and/or top to bottom (vertical) directions, but are not applied consistently between specifications and none include testing in all three directions. Initial compressive loads applied in the three loading directions range between 22 N to 150 N and the maximum compressive loads vary considerably from 90 N to 1779 N.

The rate at which the load is applied to the helmet ranges from 20 mm/min to 305 mm/min. Some standards utilize a rate of force to apply the load, these ranged from 50 N/min to 100 N/min. At the time of the investigation only US combat helmet specifications required repeated loading with 25 consecutive compression cycles. The maximum allowable deformation at peak compression ranged from 15 mm to 51 mm and the acceptable deformation at final load varied from 5 mm to 15 mm. The allowable residual deformation (a predetermined time after testing) ranges from 0.25 mm to 3.18 mm. Table 1 summarizes these findings against the new Canadian test protocol. The rationales for the values identified above were not found.

Head injuries as a result of the helmet being compressed represent a rare event. No reference documenting loading scenarios resulting in head/helmet compression was identified from the open scientific literature.

The Canadian Scientific Authority (DRDC) and Technical Authority (DSSPM) had concerns not only on permanent helmet shell compression under stress, but also on life cycle durability. Under normal use, it is expected that a combat helmet should be able to support repetitive loading without significant deformation under all field conditions. The worst test condition observed was extreme hot and this temperature was established in the protocol for product design qualification. A value based loosely on an average soldier's weight carrying a reasonably heavy load (1500 N or 153 kg) is selected to represent a soldier stepping on a helmet in the vertical direction (top-down). For the other two orthogonal directions, longitudinal and lateral, the load is reduced to approximately 75% of the force defined for the vertical direction (1100 N or 112 kg). These values are significantly higher than those found in many standards, reflecting, at least to some degree, potentially realistic loading schemes for a combat helmet during its lifecycle.

The post-conditioning assessment (ballistic testing) was added to the protocol in an effort to provide additional confidence level in the safety of the soldier and validation of the design materials and processing during lot production.

A series of test iterations was conducted to refine equipment, procedure and parameters by evaluating traditional and lightweight combat helmet designs for compression resistance. For the final validation phase presented in the following sections, helmet shells were evaluated for compression resistance under extreme hot condition. The effect of the number of compression cycles on the residual deformation and ballistic performance (back face signature - BFS) was evaluated.

Table 1. Helmet Rigidity Test Requirements

Reference	**Load Axis**	**Initial/ Final Load (N)**	**Peak Load (N)**	**Loading Rate**	**No. of Cycles**	**Def. at Peak Load (mm)**	**Def. at Final Load (mm)**	**Final Def. (mm)**	**Env. Cond.**	**Post Ballistic Test**
prEN397 [1]	side to side	30	430	100 N/min	1	40	15	-	Ambient	N/A
AS 1801-1981 [2]	side to side	-	90	-	1	15	-	-	Ambient	N/A
BS 52440 Part1 [3]	side to side	30	430	100 N/min	1	40	15	-	Ambient	N/A
ECE 324 or ECE 22.05 [4]	side to side and front to back	30	630	20 mm/min	1	40	15	-	Ambient	N/A
ISO 3873-1977 [5]	n/a	-	430	-	1	40	-	15	Ambient	N/A
PAS 015:1998 [6]	side to side	30	630	100 N/min	1	30	10	-	Ambient	N/A
US ACH, ECH [7, 8]	side to side	22	1335	305 mm/min	25	-	-	3.18 - 5min 2.54 - 24hr	Ambient	NO
	top to bottom	22	1779	305 mm/min	25	-	-	0.5 - 5min 0.25 - 24hr	Ambient	NO
LWH USMC [9]	side to side	22	1335	305 mm/min	25	51	-	3.18	Ambient	NO
	top to bottom	22	1779	305 mm/min	25	-	-	1.59	Ambient	NO
TL-8470-0004 [10]	side to side	150	900	75 N/min	1	40	5	-	Ambient	NO
SCERCAT [11]	side to side and front to back	30	630	50 N/min	1	40	15	-	Ambient	NO
Canadian CG634 GenII-Interim [12]	*side to side*	*25*	*1100*	*100mm/min*	*45*	*24*	*8*	*5 24hr*	*Hot (50°C)*	*BFS 90% New*
	front to back	*25*	*1100*	*100mm/min*	*45*	*24*	*8*	*5 24hr*	*Hot (50°C)*	*BFS 90% New*
	top/down	*25*	*1500*	*100mm/min*	*45*	*6*	*2*	*1 24hr*	*Hot (50°C)*	*BFS 90% New*

3. MATERIALS AND METHODS

Three (3) different helmet models of similar size were used to exercise the final version of the proposed test protocol. Helmet models A and B were made of novel lightweight ballistic materials while model (C) represented a standard aramid construction. The geometry was different for model A (coverage area = 1060 cm^2) in comparison with models B and C (coverage area = 1120 cm^2). All helmet samples were new and never subjected to field or laboratory conditions. Only a subset of the compression resistance and ballistic tests were conducted for the standard helmet (C) to complement data obtained previously from earlier phases of the test methodology development. The test matrix presented in Figure 1 illustrates the testing performed on each helmet model.

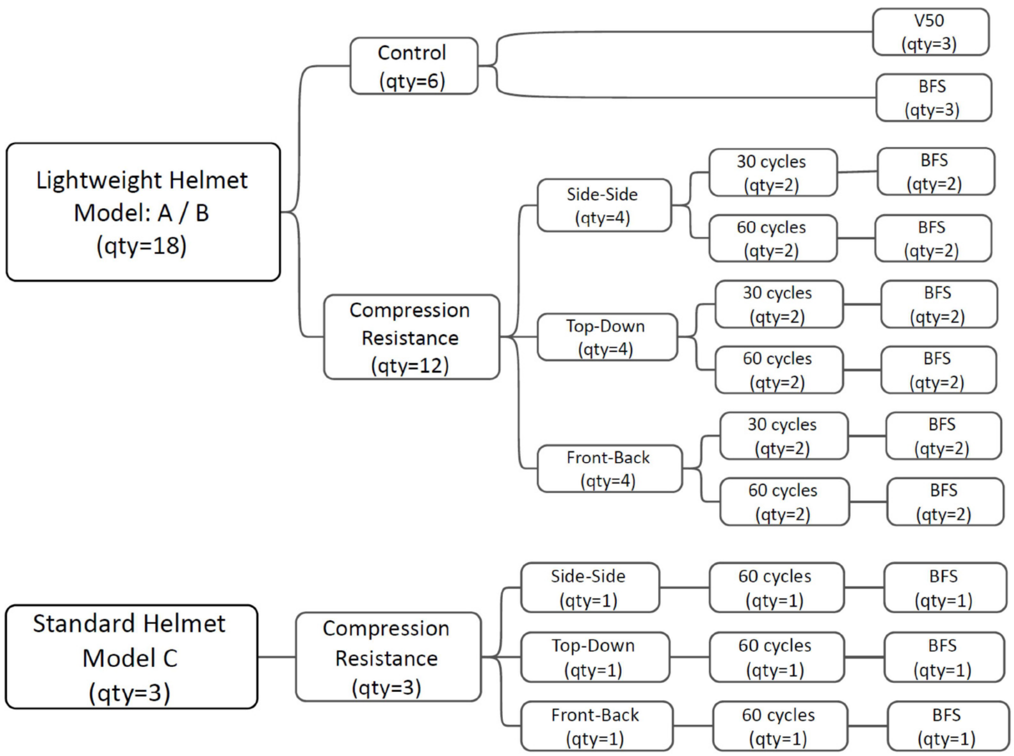
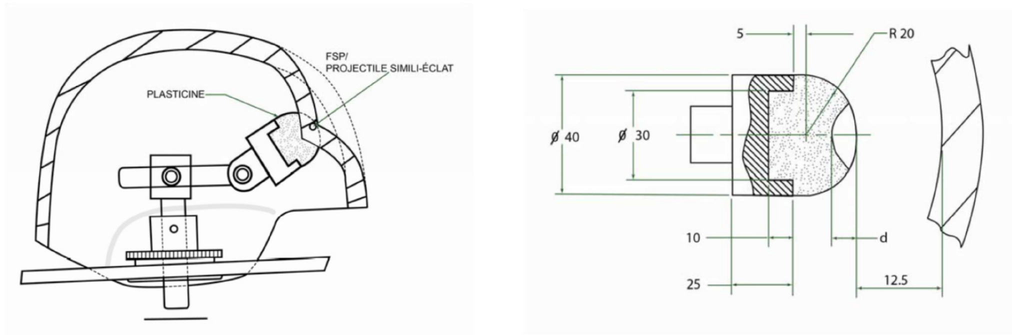


Figure 1. Test Matrix

3.1 Ballistic Testing

Baseline ballistic performance against 17 gr (1.1 g) fragment simulating projectiles (FSP) was established initially for the lightweight helmet models (control). Helmet shells (no pad and retention system) were tested for ballistic limit (V_{50}) and back face signature (BFS) using the procedure described in the "Technical Purchase Description - Helmet, CG634 Generation II - Interim (Industry Draft Release)"[12]. The same support fixture was used for V_{50} and BFS evaluations to firmly clamped helmet shells on their two opposite side brims as referred in STANAG 2920 [13]. For V_{50} testing, a 50 mm diameter witness plate (Al 2024T3, 0.5 mm thick) located 50 mm behind and parallel to the area of impact was used to detect perforation. Up to 10 shots per helmet was required to obtain 3 complete and 3 partial perforations within a 40 m/s range. For BFS testing, the witness plate was replaced with hemispherical shaped clay located 12.5 mm behind the impact location as indicated in Figure 2. BFS was assessed at five locations on the shell (front, back, left, right, and crown) against 17 gr FSP at striking velocities between 580 and 640 m/s.

Due to the limited quantity of helmet samples available, the effect of compression resistance testing on the ballistic performance was only evaluated for BFS. No post-compression ballistic limit (V_{50}) tests were performed in this study.



Helmet Support Fixture

Witness Clay Hemisphere

Figure 2. Back Face Signature Test Setup

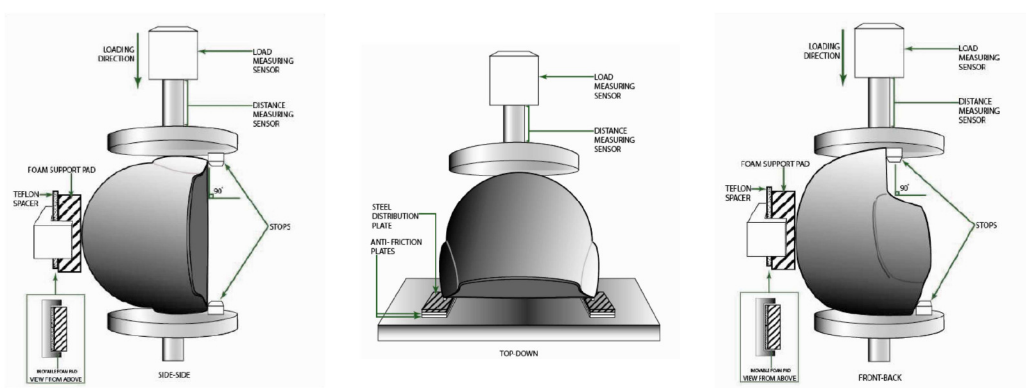
3.2 Compression Resistance Testing

Helmet shells were evaluated for compression resistance using the procedure described in the "Technical Purchase Description - Helmet, CG634 Generation II - Interim (Industry Draft Release)"[12]. Each sample was evaluated for one direction only (side-side or top-down or front-back).

Helmet width "**A**" (side-side, top-down, front-back as required) was measured before conditioning the samples at 50ºC for 18 hours. Helmet shells were then placed on a rigidity tester as shown in Figure 3. A 25 N pre-load was applied and the width "**A***" was measured. Test samples were compressed at a rate of 100 mm/minute until a load of 1100 N (for side-side and front-back) or a load of 1500 N (for top-down) was reached. The compression load was then reduced to 25 N. This sequence was repeated until all cycles (30 or 60) were completed. During the final cycle (30^{th} or 60^{th} as applicable), the width "**B***" with the helmet under maximum load and the width "**C***" with the helmet under minimum load (25 N) were measured.

The unloaded helmet width "**C**" was measured after taking the samples out of the rigidity tester and 90 min after removal from the conditioning chamber. Unloaded helmet width "**D**" was measured 24 hours later. The following deformation values were calculated from the measurements:

a) Maximum deformation under load (B*-A*)
b) Permanent deformation under preload (C*-A*)
c) Permanent deformation unloaded (C-A)
d) Restitution value after a 24 hour recovery period (D-A)



Side-Side

Top-Down

Front-Back

Figure 3. Compression Test Setup

4. RESULTS

The areal density (kg/m^2) was used for comparing helmet mass since the geometry (coverage area) differed for the three models tested. The areal density of the composite shell materials was estimated at 8.5, 7.7, and 10.3 kg/m^2 for models A, B, and C, respectively (Figure 4). Note that helmets A and C were finished (painted) while model B was supplied unpainted so the actual difference in areal density between model A and B would be less than the reported value. Average shell weight data are presented in Figure 5.

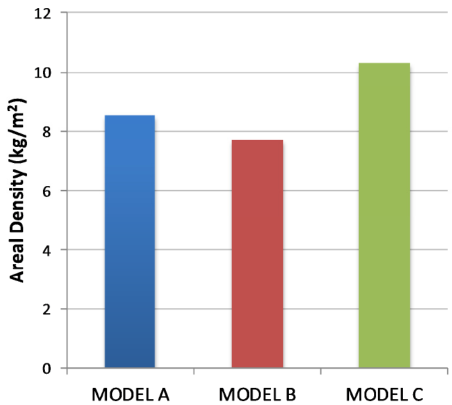


Figure 4. Areal Density

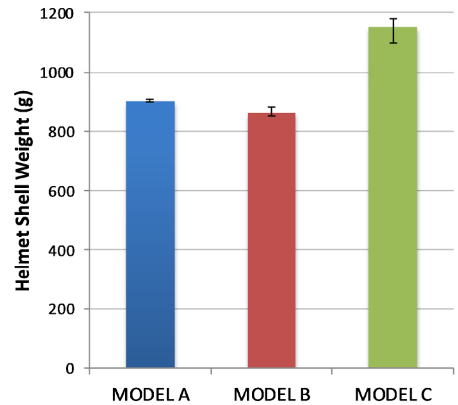


Figure 5. Average Shell Weight

4.1 Ballistic Limit

The V_{50} test results (Figure 6) confirmed the increased ballistic perforation resistance of the two lightweight helmet models (A and B) over the standard aramid construction (C). But the true gain in performance is better portrayed using the ratio between V_{50} and areal density, proposed as a measure of ballistic efficiency (Equation 1). Normalizing the ballistic limit data with the areal density allowed comparing materials while including both ballistic performance and weight characteristics. Increases in ballistic efficiency of 34% for model A and 52% for model B were observed over the standard aramid helmet (Figure 7).

$$Ballistic\ Efficiency_n = \frac{V50_n}{AD_n} \quad \textbf{(1)}$$

where n = A, B, or C

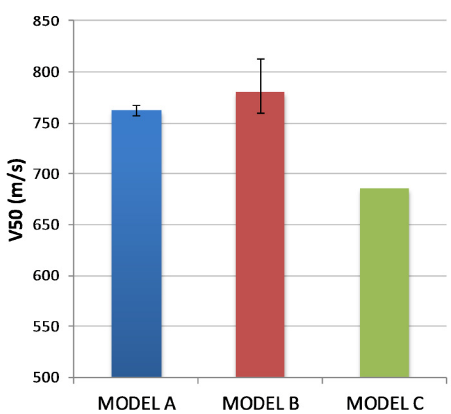


Figure 6. Ballistic Limit

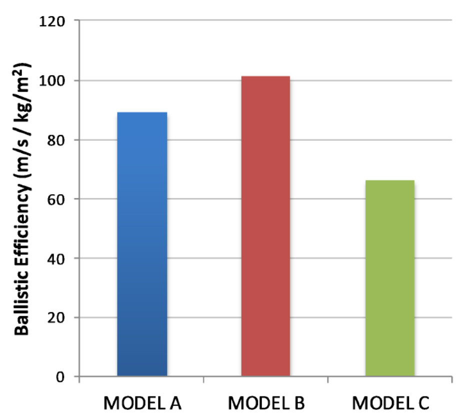


Figure 7. Ballistic Efficiency

4.2 Compression Resistance

For side-to-side and top-down compressions, larger deformations were observed for helmet model A (Figure 8 and Figure 9). Surprisingly, helmet model C exhibited larger deformation under front-to-back compression. This tendency was confirmed with another sample tested under similar conditions (Figure 8) although the difference was not as important for the second model C tested. This result was later attributed to the fact that helmet C was the only model with a frontal lip which provided less support during front-to-back loading cycles. In general, the trend observed for the maximum deformation under load was replicated for the restitution value measured after 24 hours.

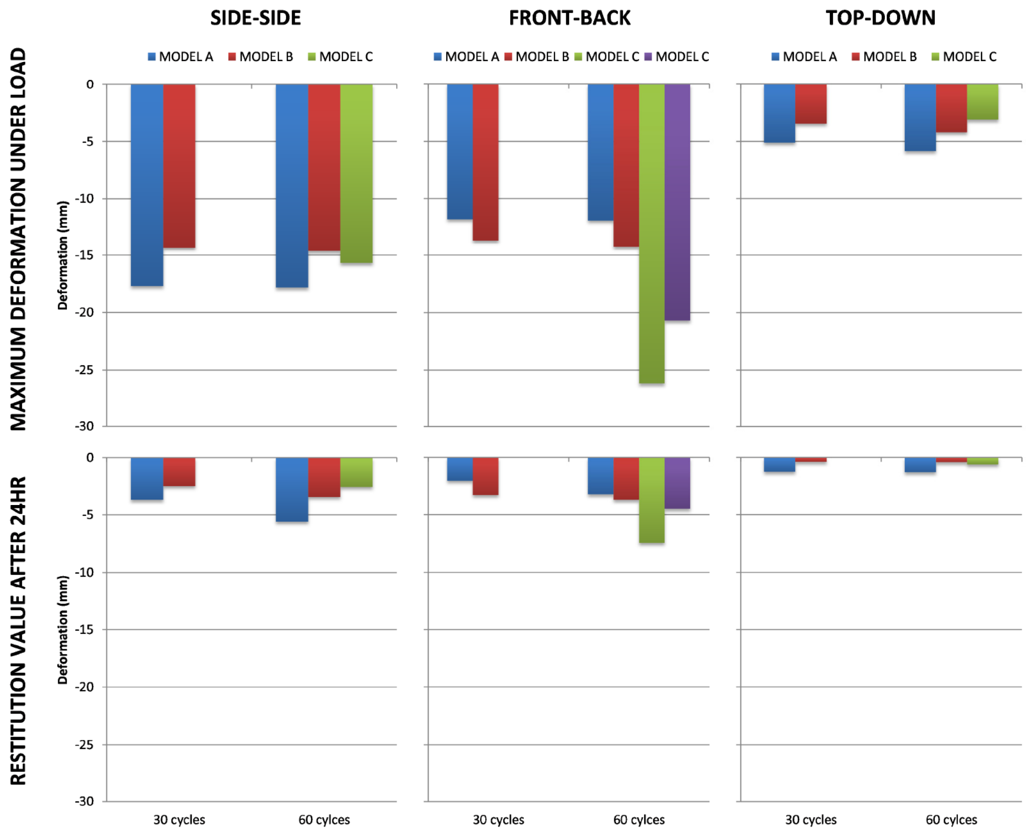


Figure 8. Helmet Deformation

As indicated by the difference between the first and last compression cycle (Figure 9), a larger reduction in deformation was observed for the lightweight helmets tested. This is particularly obvious for the top-down orientation where the difference in peak deformation under load between the first and last cycle is 4.5 times greater for the lightweight model A in comparison with the standard aramid helmet. Note that there were geometrical differences between all three helmet models tested which may also account for the noted differences in stiffness.

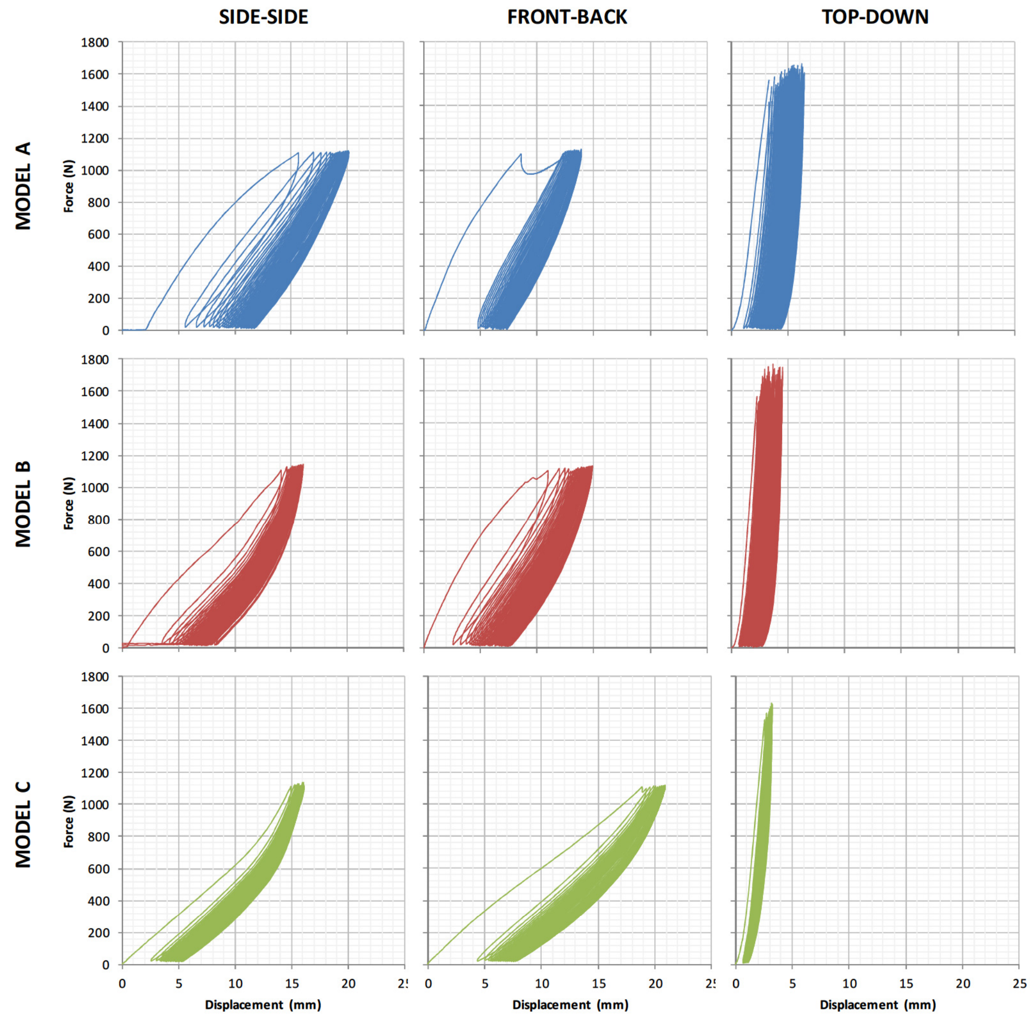


Figure 9. Force-Displacement (60 Cycles)

4.3 Back Face Signature

Back face signature data were averaged to compare the different test conditions (Figure 10). The BFS value for helmet model C without prior compression testing (0 cycle) was provided by DSSPM and obtained during previous test series. Despite the large variability in the results, cyclic compression loading had a detrimental effect on the BFS for the two lightweight helmet models tested. The same trend was not observed for helmet C due to the limited data. Interestingly, the helmet model having the highest ballistic limit (B) also had the largest normalized BFS values.

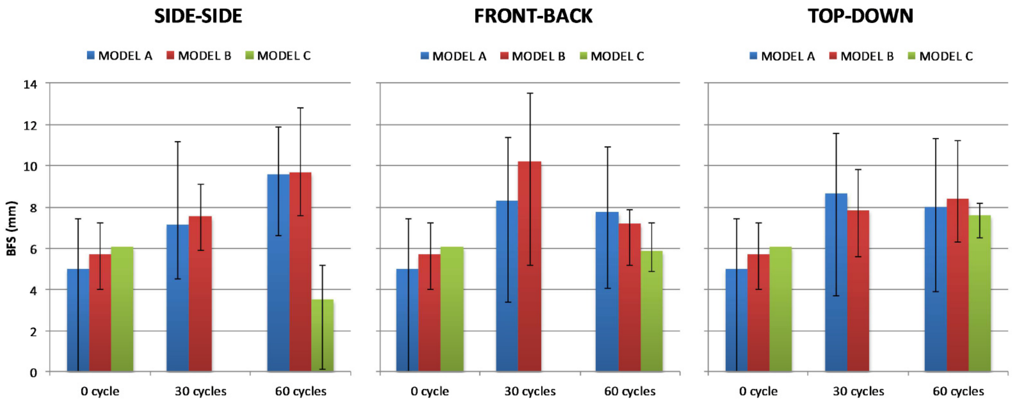


Figure 10. Back Face Signature

5. CONCLUSIONS

Three helmet models, including traditional design and novel lightweight technologies, were used to evaluate a proposed compression test protocol for assessing the ability of combat helmets to support repetitive loading under conditions that challenge the helmet shell's structural integrity.

The results and observations collected were instrumental in the definition of final parameters and performance requirements to support future acquisition efforts. As such, the compression resistance methodology described in the Technical Purchase Description - Helmet, CG634 Generation II - Interim (Industry Draft Release) [12] requires test samples to be subjected to 45 compression cycles for all three orientations. The selection of the orthogonal directions allows repeatable testing while challenging the helmet in a way to minimize the possibility that a weakness in a helmet structure is left undetected. The force-deflection curves indicated that significant damage occurred after the first 30 cycles but not enough to justify going up to 60 cycles. Peak loads were maintained to 1100 N (for side-side and front-back) and 1500 N (for top-down). The rate of compression was kept at 100 mm/minute. The maximum allowable deformation at peak compression was set to 24 mm (for side-side and front-back) and 6 mm (for top-down) and the acceptable deformation at final load was confirmed at 8 mm (for side-side and front-back) and 2 mm (for top-down). Finally, the allowable deformation under no load (24 hours after testing) was established at 5 mm (for side-side and front-back) and 1 mm (for top-down). While these performance requirements are achievable by the latest combat helmet technologies, the proposed compression resistance testing should help to ensure that a minimum level of rigidity is maintained without increasing the weight or affecting the ballistic performance over the lifecycle of the helmet.

While the compression test parameters were derived from existing product specifications and experimental findings, the link with an actual operational scenario remains to be established and may involve further changes to loads, loading rates, and number of cycles. This will require instrumenting a set of helmets to gather 'real world' quasi-static loading over a period of months during storage, transport, handling, training and operations. Until such information is made available, it would be difficult to extrapolate from the compression test set-up to an operational scenario.

Nevertheless, the proposed compression resistance test protocol is the latest attempt to ensure a structurally sound shell by challenging the helmet construction to eliminate designs that are prone to damage growth and performance degradation.

Acknowledgments

The author would like to thank Mr. Gilles Pageau (Defence R&D Canada - Valcartier) for his valuable advice during review of existing helmet rigidity requirements.

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